

Program ID: RGNTA

Title: Coordinated Observations of Interacting Peculiar Red Giant Binaries - I

PI: T.B. Ake

Results:

IUE observations were begun for a two-year program to monitor the UV variability of three interacting peculiar red giant (PRG) binaries, HD 59643 (C6,2), HD 35155 (S3/2), and HR 1105 (S3.5/2.5). All of these systems were suspected to involve accretion of material from the PRG to a white-dwarf secondary, based mainly on previous IUE investigations. From our earlier surveys of PRGs, they were primary candidates to test the hypothesis that Tc-poor PRGs are formed as a result of mass transfer from a secondary component rather than from internal thermal pulsing while on the asymptotic red giant branch.

The IUE observations were coordinated with H alpha observations of these systems by one of the proposers. Prior to this project, HR 1105 had an optically determined, 596-day orbit (Griffin, 1984, Obs., 104, 224), while the other stars had unknown periods. Other observers, notably Jorissen and his collaborators, were actively measuring the radial velocities of these stars in hopes of determining orbital parameters (e.g., Jorissen & Mayor, 1992, A&A, 260, 115). All were UV variable, and along with the H alpha observations, this project was to establish the source and physical conditions of the UV variations with orbital phase. For example, in our publication on the companion to HD 35155 (Ake, Johnson and Ameen 1991), we postulated that HD 35155 may undergo eclipses because of a UV minimum seen in the IUE data. Subsequently, Jorissen et al (1992, IBVS, 3730), came to a similar conclusion from optical photometry, indicating the bulk of the UV flux came from a small secondary in this system.

During this period, HR 1105 was also being actively monitored from the ground by others. Shcherbakov & Tuominen (1992, A&A, 255, 215) found H alpha to be orbitally modulated, and that from profiles seen near conjunction, streaming occurs between the components.

Due to the long periods of these objects, detailed analyses could not be completed until the second year of observations were made.

Publications:

"An Interactive Companion to the S Star HD 35155", T.B. Ake, H.R. Johnson, and M.M. Ameen 1991, ApJ, 383, 842.



## AN INTERACTIVE COMPANION TO THE S STAR HD 35155

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### ABSTRACT

Although relatively unremarkable in the visual, the S star HD 35155 (S3/2) shows strong emission lines of multiply ionized species and excess continuous emission shortward of 2000 Å. Several ultraviolet spectra have been taken with *IUE* and analyzed. We find that the UV source is highly variable in the *IUE* region even though Eggen reported it in 1972 to be photometrically constant at optical wavelengths. Subtraction of the observed flux of a similar, single S star (HR 8714) from the ultraviolet spectrum yields a curve of excess emission which is close to a simple  $f_{\lambda} \sim \lambda^{-1}$  power law instead of a blackbody curve, pointing to its probable production by a cloud radiated by a hot source. There is nevertheless weak evidence for a characteristic temperature near 15,000 K for the secondary. The integrated excess flux at minimum light amounts to a luminosity of 0.2  $L_{\odot}$  at the prescribed position of the source—far too much for a white dwarf—which confirms that the excess ultraviolet light originates in a source other than the photosphere of the companion. Measurement of the emission lines indicates that they are formed in different regions of the system, with permitted lines, such as C IV, coming from a rapidly rotating accretion disk and semiforbidden lines, such as Si III] and C III], from a cloud. Of particular interest is the absence of He II 1640 Å, indicating the lack of a hot boundary layer of the disk. A blue cutoff on the Mg II lines indicates mass outflow, and several considerations place the hot gas in the matter thrown off by the S star. Consequences for the evolution of the S star are unclear, but there is a strong presumption that the chemical peculiarities of the red giant are due to mass transfer from a WD companion when the companion itself was an AGB star. The system may be related both to the Ba stars and the symbiotic stars.

**Subject headings:** spectrophotometry — stars: binaries — stars: individual (HD 35155) — stars: S-type — ultraviolet: spectra

### 1. INTRODUCTION

Among the chemically peculiar red giants, S stars, the atmospheres of which are enriched in *s*-process elements but still have  $C/O < 1.00$ , seem to constitute a transitional evolutionary link between the M giant stars and the carbon stars (Bessell, Wood, & Lloyd Evans 1983; Wood 1985; Lambert 1989). Their spectral classification has been reviewed by Ake (1979) and Keenan & Boeshaar (1980). Several S stars have been identified with objects in the AFCRL and IRC sky surveys (Wing & Yorka 1977), and some information regarding population types and Galactic distribution are now available from visual spectra (Yorka & Wing 1979) and *IRAS* observations (Jura 1988; Kleinmann 1989). Broad-band photometry and estimates of luminosity, reddening, effective temperature, and distance for several S stars have been given by Eggen (1972). A few model atmospheres are available (Piccirillo 1980; Johnson 1982), and several interpretations of S-star spectra have been offered (Scalo & Ross 1976; Wyckoff & Clegg 1978; Piccirillo 1980). Chemical compositions for several S stars have been recently published (Smith & Lambert 1985, 1986, 1990; Dominy & Wallerstein 1987).

In the course of an *IUE* investigation of S stars, we discovered intense UV emission from ions indicative of a state of

high ionization in the S star HD 35155, an otherwise ordinary appearing star of apparent visual magnitude 6.77 and spectral class S3/2 (Keenan & Boeshaar 1980). It was one of only two photometrically constant S stars among the sixteen studied with broad-band photometry (Eggen 1972); narrow-band photometry is also available (Wing 1967). The star is present as IRC 10086 in the Caltech Two Micron Sky Survey (Neugebauer & Leighton 1969) at  $K = 2.07$ . A fairly secure value of  $T_{\text{eff}} = 3600$  K has been obtained by one of the authors (H. R. J.) from model fitting to complete spectrophotometry (1.2–4.5  $\mu\text{m}$ ) obtained with the Kuiper Airborne Observatory (G. C. Augason 1982, private communication) and from the infrared-flux method (Blackwell & Shallis 1977; Blackwell, Petford, & Shallis 1980).

By fitting with giant branches of old disk population stars, Eggen estimated  $M_{\text{bol}} = -3.1$ , a distance of 372 pc, and from nearby B stars, a reddening of  $E(B-V) = 0.03$ . Then  $L_{\star}/L_{\odot} = 1.22 \times 10^3$ . With no independent way of measuring the distance or absolute magnitude, we adopt these values for our analyses. The effective temperature and luminosity, which are reasonable for an M3 giant, place HD 35155 in the clump of similar M and S stars observed by Smith & Lambert (1985, 1986) and would imply a mass in the range 1.5–3.0  $M_{\odot}$ . A change of a factor 2 in either direction in the distance would move HD 35155 well outside the clump of similar stars in the H-R diagram. There is no evidence whatever for such changes, and we believe the distance quoted must be accurate within a factor of 1.5.

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TABLE 1  
JOURNAL OF OBSERVATIONS

Mid-Exposure Date/Time	(UT)	Image Number	Dispersion Mode	Exposure Time (minutes)	$m_{\text{FES}}$
1982 Dec 27 .....	03:54	LWR 14924	L	45	6.84
	09:34	LWR 14928	L	8	6.81
	09:46	SWP 18897	L	10	...
1983 Jan 6 .....	21:39	SWP 18957	L	60	6.93
	23:00	LWR 15008	H	90	6.89
1983 Aug 5 .....	10:34	LWR 16528	L	8	6.93
	11:11	SWP 20615	L	95	6.92
	12:47	LWR 16529	L	85	6.96
1983 Sep 1 .....	15:47	LWR 16715	L	13	6.97
	17:17	SWP 20878	L	240	6.97
	20:02	LWR 16716	L	60	6.92
	20:58	SWP 20879	L	68	6.93
1984 Mar 19 .....	19:27	LWR 17305	L	8	6.88
	20:06	SWP 22522	L	60	6.88
	20:57	LWR 17306	L	30	6.87
1984 Apr 1 .....	12:57	SWP 22638	H	400	6.78
	16:45	LWR 17334	H	75	6.83
1984 Apr 3 .....	10:01	LWR 17337	L	30	6.78
	10:51	SWP 22656	L	60	6.79
	13:34	LWR 17338	H	260	6.79
1985 Jan 21 .....	00:08	LWP 5239	L	7	6.88
	01:01	SWP 24937	L	90	6.88
	02:03	LWP 5240	L	25	6.89
1987 Nov 13 .....	10:43	LWP 12082	L	15	6.77
1987 Nov 17 .....	19:57	SWP 32352	L	63	6.80
1987 Nov 20 .....	04:04	LWP 12131	L	10	6.82
1987 Nov 22 .....	04:47	SWP 32376	L	35	6.82
	06:43	SWP 32378	L	25	6.78
1987 Dec 17 .....	18:06	SWP 32551	L	35	6.62

From the luminosity and  $T_{\text{eff}}$ , the stellar radius is found to be  $90 R_{\odot}$ . Using the visual-surface brightness relation (Barnes, Evans, & Moffett 1978) and converting Eggen's colors from the Kron to Johnson photometric system as prescribed by him, we find a radius of  $109 R_{\odot}$ . Thus the radius is about  $100 R_{\odot}$ .

Because neither photospheres nor chromospheres of S stars are expected to produce multiply ionized ions, the most straightforward explanation of the emission seen with *IUE* is a hot, nearby, compact companion, whose presence also appears to be revealed by excess continuous emission shortward of  $2500 \text{ \AA}$ . As a Tc-deficient S star (Peery 1971; Smith & Lambert 1990) with an interacting companion, HD 35155 is an unusual object perhaps linked to both Ba stars and to symbiotic stars. A description and interpretation of the ultraviolet spectrum and some inferences regarding the compact companion and the possible locations of the source of the emission lines are the subject of this paper, which greatly extends our preliminary survey (Johnson & Ake 1984). In § 2 we describe the observations. In § 3 we analyze the spectra. Section 4 discusses the compact companion. Section 5 analyzes the hot gas clouds. In § 6 we consider possible scenarios for the production of the observed characteristics.

## 2. OBSERVATIONS

Exposures were taken with the LWP, LWR, and SWP cameras through the large aperture to measure absolute fluxes, and the data were reduced at the Goddard Regional Data

Analysis Facility. Table 1 lists the dates, camera image numbers, dispersion mode, exposure times, and FES magnitudes. Due to the limited dynamic range of the cameras, more than one observation was required to maximize the exposure levels of various features. An atlas of nearly simultaneous LW and SW low-resolution spectra is displayed in Figure 1.

The hot companion was discovered during a survey with the *IUE* of Mg II chromospheric emission in S stars (Johnson & Ake 1984) when the continuum flux in the LWR image was found to extend, uncharacteristically for red giants, to  $2000 \text{ \AA}$ . A subsequent underexposed SWP exposure displayed C IV in emission and confirmed the presence of the ultraviolet continuum excess (Fig. 1a). A second, deeper SWP spectrum taken 9 days later was characterized by a wealth of emission lines (Fig. 1b). The continuum also had dropped by 0.5 mag, and strong absorption features had appeared. The emission spectrum is similar to such other late-type stars with interacting hot companions as symbiotic stars (Kenyon 1986), several Ba stars (Böhm-Vitense 1980; Schindler et al. 1982; Dominy & Lambert 1983; Böhm-Vitense & Johnson 1985), HD 352 = 5 Cet (Eaton & Barden 1987), the carbon star HD 59643 (Johnson et al. 1988), and the recurrent nova T CrB (Cassatella et al. 1982). The absorption spectrum somewhat resembles that of  $\zeta$  Aur-like systems where a hot secondary is partially obscured by the outer layers of a cooler supergiant.

Due to the possibility that an eclipse had been taking place, new observations were obtained 8 months later. They indi-

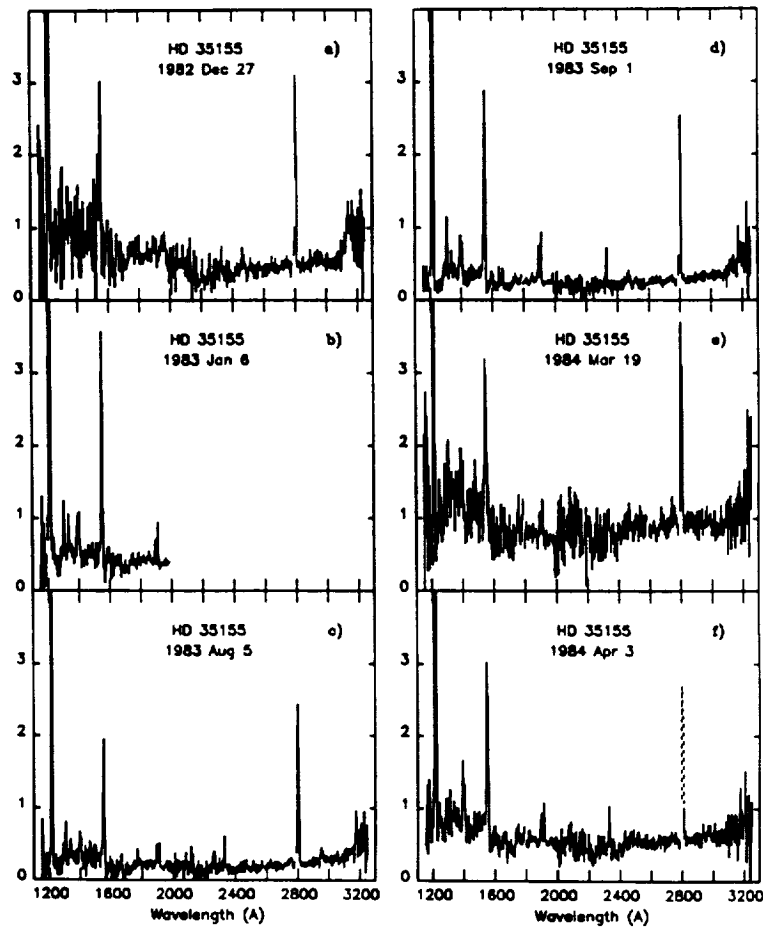


FIG. 1.—*IUE* low-dispersion spectra of HD 35155. All plots are on the same scale ( $\times 10^{-13}$  ergs  $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ ) to emphasize the degree of variation. Dotted lines are overexposed regions and thus are underestimates of the true flux.

cated a further decrease in light levels for both the emission lines and the continuum (Fig. 1c), but 1 month later the lines were nearly as strong as earlier (Fig. 1d), while the continuum brightened only moderately. The different behavior of the continuum and emission lines suggest that HD 35155 is either a highly active system with variations occurring in the region of formation of the ultraviolet lines and continuum on a time scale of a few weeks or less, or is an eclipsing system where, due to stratification effects, regions with differing physical conditions are being occulted at different times. Thus further observations were taken occasionally during our other *IUE* programs to monitor this system (Figs. 1e–1f).

### 3. ANALYSIS OF THE SPECTRA

#### 3.1. Description of Spectra

In low dispersion, the spectra are exceedingly complex, showing both emission lines and absorption features. In Figure 2, we identify the emission lines seen in a particularly intense state. The Mg II  $\lambda 2800$  and C IV  $\lambda 1550$  resonance lines are always the strongest features. Also noted are several absorption features from 1400 to 1750 Å that are prominent in  $\zeta$  Aur-like systems during partial eclipse (e.g., Ake, Parsons, & Kondo 1985; Eaton 1991) and can be identified with blends due mainly to Fe II (Table 2). The absorption lines further

complicate the spectra by creating local high points that occur in relatively line-free regions between the features, such as at 1429 and 1596 Å, which resemble additional emission lines.

Although Eggen reported no optical variability, HD 35155 varies dramatically in the ultraviolet, both in the level of the continuum and the emission and absorption lines seen, which rules out the photosphere of a hot companion as the source (though not the cause) of the ultraviolet radiation. At times the emission spectrum changes with no corresponding change in the continuum (Fig. 1i vs. Fig. 1k), while at others the lines stay approximately constant while the continuum rises and falls to cover and expose them (Fig. 1e vs. Fig. 1f).

Overall the continuous spectrum is remarkably flat, especially at epochs of quiescence, resembling in certain ways the ultraviolet spectra of both symbiotic systems and other inter-

TABLE 2  
ABSORPTION BLENDS FROM 1400 TO 1750 Å

Wavelength (Å)	Ion and Multiplet
1403–1426 .....	Fe II, Ni II, Ti II
1435–1445 .....	Fe II, Ni II, Ti II, Co II
1558–1589 .....	Fe II (44–46)
1608–1655 .....	Fe II (8, 43, 44, 68)
1670–1726 .....	Fe II (37–41, 84–85)

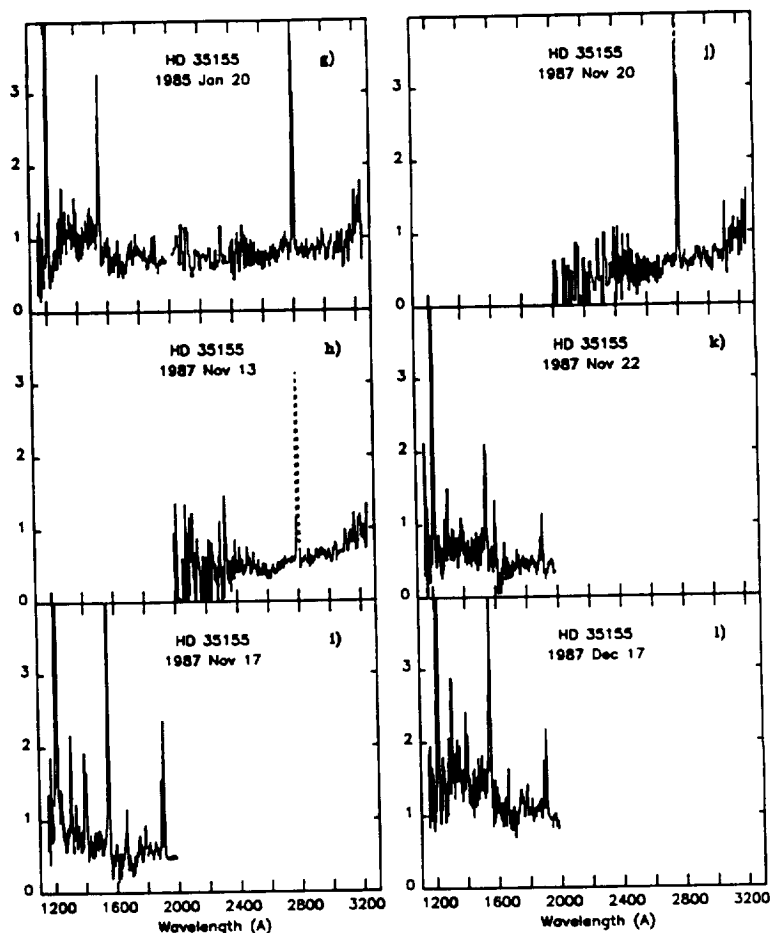


FIG. 1—Continued

acting binaries. Specifically, on the spectra with the lowest flux levels (1983 Aug 5 and Sep 1), the energy distribution is virtually flat between 2700 and 1400 Å. At epochs of greater activity, the flux is flat from 2700 to 1800 Å and then increases toward a peak at 1300 Å. From the few spectra available, there is no convincing evidence of periodicity.

The crossover wavelength where the fluxes from the two stars are equal occurs in the region 3000–3200 Å, depending somewhat upon the state of excitation of the secondary. The flux gradient of the S-star photosphere in the ultraviolet region is so steep that at 2700 Å it contributes less than half of the light, and at 2000 Å virtually all the light arises from the secondary or the cloud. The lack of a prominent 2200 Å dip indicates the reddening is small, and we adopt Eggen's value of  $E(B-V) = 0.03$  and the average reddening law of Savage & Mathis (1979) to correct the data.

### 3.2. Continuous and Absorption Spectra

Locating a true continuum for a spectrum of such complexity as the *IUE* low-resolution spectra is nearly impossible. We have chosen points between well-known emission lines as well as pseudocontinuum peaks between absorption features as being most representative. Table 3 displays the fluxes at 1430, 1595, and 1950 Å. A power-law fit ( $f_\lambda = C\lambda^\alpha$ ) was then made through these to attempt to characterize the changes in the continuum. Two such fits are shown in Figure 3. After subtrac-

ting a scaled spectrum of the  $S4^+/1^+$  star HR 8714 in the LW region, we find that in its low state (Fig. 3a) the spectrum can be well represented over the entire 1300–3300 Å region by the power law. In its high state, however, there is additional flux longward of 2400 Å that is not accounted for by this fit (Fig. 3b).

We find that  $-1.0 < \alpha < -1.5$  in all spectra (Table 3) regardless of the level of activity. Within the errors, we can say that the flux,  $f_\lambda$ , decreases like  $\sim \lambda^{-1.2}$ , much more slowly than either the Rayleigh-Jeans flux of a hot star ( $f_\lambda \sim \lambda^{-4}$ ) or the flux of a steady state accretion disk ( $f_\lambda \sim \lambda^{-2.3}$ ; see Pringle 1981). This is quite reminiscent of the carbon star HD 59643 (Johnson et al. 1988) which has  $f_\lambda \sim \lambda^{-1.7}$  and has no obvious interpretation.

As an indicator of absorption-line variability, we have measured a "pseudo-equivalent width,"  $EW(1700)$ , of the strong absorption trough at 1700 Å between the O III] 1663 Å and N III] 1750 Å emission lines. We integrate the relative depression in a 60 Å band centered at 1700 Å using the power-law parameters to determine the continuum level. The measurements are listed in Table 3 and are shown in Figure 4. We find that the absorption is anticorrelated with the brightness of the continuum, as represented by the flux at 1950 Å. Implications of this behavior are discussed in § 4.

Finally we show in Figure 5 an apparent trend of ultraviolet flux with visual magnitude as measured by the FES, in the

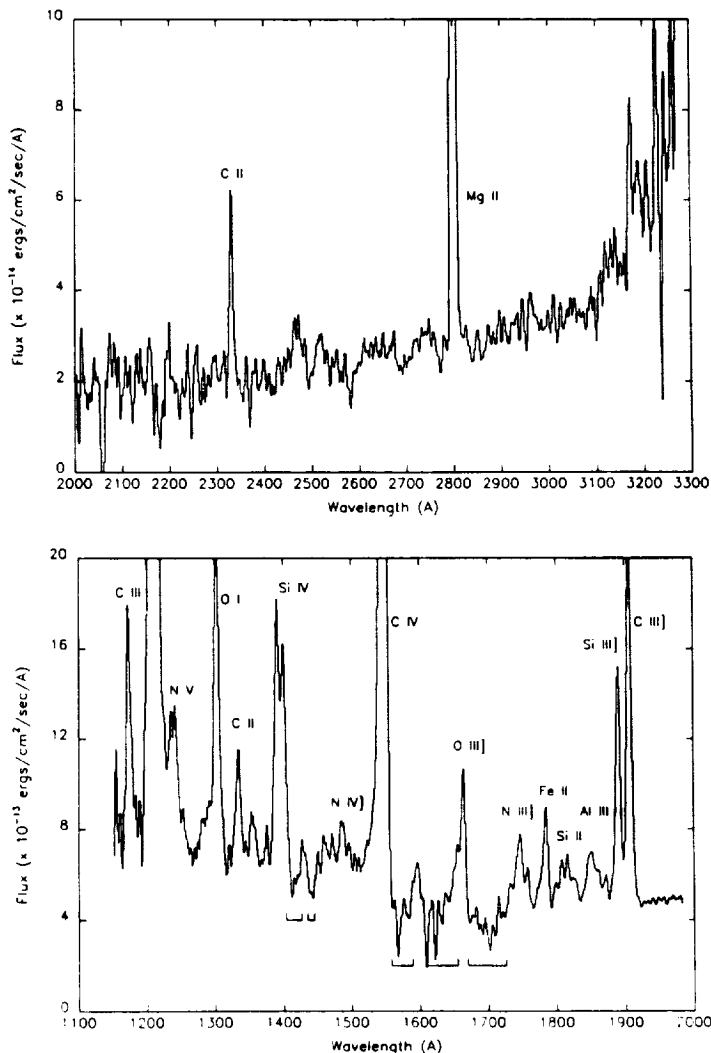


FIG. 2.—Prominent spectral features in HD 35155 for LWR 16716 (upper) and SWP 32352 (lower). The strongest emission lines are identified; absorption features (see Table 2) are shown by brackets under the spectra.

sense that the star is optically brighter at brighter UV phases. Thus even at optical wavelengths the secondary contributes slightly to the flux. The fact that Eggen found no optical variability may indicate that HD 35155 goes through periods of long-term quiescence.

### 3.3. Emission Lines

Integrated fluxes of the strongest emission lines are presented in Table 4 for the SWP spectra and in Table 5 for the LW region. Most of these features are uncommon in red giants. The Mg II  $\lambda 2800$ , C II  $\lambda 2325$ , and O I  $\lambda 1300$  lines are seen in the chromospheres of single M giants, but are enhanced in HD 35155. We estimate the proportion of the Mg II flux from the S-star chromosphere using the measured ratio of Mg II to the bolometric flux,  $F_{\text{Mg II}}/F_{\text{bol}}$ , in M giants (Steiman-Cameron, Johnson & Honeycutt 1985). This ratio has the advantage of being independent of distance, though not of reddening. For a star of the color of HD 35155 ( $V-K = 4.7$ ),  $F_{\text{Mg II}}/F_{\text{bol}} = 2.5 \times 10^{-6}$ . Using Eggen's data and the data in Table 5, we calculate a value of  $1 \times 10^{-5}$  for HD 35155. Thus it appears that even in the chromospheric lines much of the flux does not arise from the S star in the system.

In addition to the low-dispersion spectra, we have obtained one SWP and three LWR high-resolution spectra. In the SWP spectrum, the intersystem lines Si III]  $\lambda 1892$  and C III]  $\lambda 1909$  are well exposed, and C IV  $\lambda 1548, 1550$  is undoubtedly present as a broad region of emission. Mg II is the most prominent feature in the LWR spectra.

The strongest lines from the high-dispersion spectra are displayed in Figures 6–8, and radial velocities and velocity widths are given in Table 6. We note that while C IV is the strongest feature in the low-dispersion spectra, where it varies by a factor of 3, it is nearly completely washed out in the high-dispersion spectrum due to broadening. The other strong permitted lines in low dispersion must suffer the same fate as they are not apparent at all. We attempted to fit the C IV blend with Gaussian profiles to model rotational broadening, but the redward side of C IV is contaminated by Fe II absorption (Fig. 6). We find its FWHM is  $> 2500 \text{ km s}^{-1}$ .

Si III] and C III] are narrow and sharp (Fig. 7), with a FWHM of  $73 \text{ km s}^{-1}$  for C III] and  $103 \text{ km s}^{-1}$  for Si III]. At half-maximum flux, the widths of Si III] and C III] are  $\sim 90 \text{ km s}^{-1}$ , corresponding to a Doppler velocity of  $55 \text{ km s}^{-1}$ . This is at least twice as great as the widths of chromospheric lines in other cool giants (e.g., Judge 1986a, b; Eaton & Johnson 1988).

This is clear evidence that Si III] and C III] are nebular—produced either in the outer edge of an accretion disk, a gas stream or cloud, or the chromosphere of the giant—while C IV arises from a rapidly rotating region. That the velocity width of C IV greatly exceeds that of Si III] and C III] is strikingly similar to the interactive carbon star HD 59643 (Johnson et al. 1988), but is dramatically different from the situation in Mira B

TABLE 3  
CONTINUUM AND ABSORPTION-LINE MEASURES

SWP Image Number	$f_{1430}^a$	$f_{1595}^a$	$f_{1950}^a$	EW(1700) (Å)	$\alpha$	C
18897.....	0.88::	0.78::	0.56:	14.1:	-1.48	4.22(-9)
18957.....	0.550	0.472	0.365	16.1	-1.05	1.03(-10)
20615.....	0.303	0.228	0.197	26.5	-1.31	3.79(-10)
20878.....	0.335	0.325	0.242	19.1	-1.10	1.03(-10)
22522.....	1.14	1.02	0.711	12.9	-1.49	5.84(-9)
22656.....	0.744	0.697	0.517	17.3	-1.21	5.11(-10)
24937.....	0.976	0.870	0.675	12.5	-1.20	5.92(-10)
32352.....	0.698	0.611	0.491	21.7	-1.12	2.53(-10)
32376.....	0.634	0.555	0.397	16.0	-1.52	4.29(-9)
32551.....	1.37	1.23	0.934	9.8	-1.25	1.24(-9)

<sup>a</sup>  $\times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$ .



TABLE 4  
SWP REGION EMISSION-LINE FLUXES ( $10^{-13}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$ )

SWP Image Number	N v $\lambda 1237$	O I $\lambda 1303$	C II $\lambda 1335$	Si IV $\lambda 1398$	C IV $\lambda 1549$	O III] $\lambda 1663$	Si III] $\lambda 1892$	C III] $\lambda 1909$
18957.....	1.0:	4.68	1.82	8.53	30.5	...	2.58	3.89
20615.....	0.9:	2.66	1.27	4.15	18.2	...	1.88	2.25
20878.....	...	3.93	2.01	7.94	26.7	1.72	3.23	4.41
22522.....	...	...	...	...	28.2	...	2.67	3.57
22638 <sup>a</sup> .....	...	...	...	...	...	...	4.15	6.68
22656.....	...	...	1.2::	9.92	25.7	...	4.06	4.43
24937.....	...	3.12	...	3.75::	19.8	...	2.35	2.70
32352.....	5.9	13.2	3.94	16.9	55.4	4.58	8.29	14.6
32376.....	...	4.81	1.05	4.7:	21.1	2.13:	3.77	6.99
32551.....	...	8.98	2.45	8.16	38.9	3.65	6.17	9.62

<sup>a</sup> High-dispersion image.

Although He II is absent, He I 10830 Å has been observed to have a strong P Cygni profile in HD 35155 (Brown et al. 1990). In fact, these authors clearly connect the appearance of He I 10830 and large radial velocity variations in S and MS stars with the lack of Te and infer that the Te-deficient S and MS stars are "accidental" S stars in which the enhancement in s-process elements has been produced by earlier mass transfer (§ 6). We still lack a careful treatment of NLTE radiative transfer which would explain the appearance of He I 10830 and the lack of He II 1640. We should, however, remark that He I 10830 can also be excited by the mild-shock waves which result from acoustic waves generated by convection and therefore must transverse the atmospheres of most red giants (Cuntz & Luttermoser 1991). This would presumably explain the weak and variable line seen in many M giants and other S stars, but not the strong lines seen in such binary stars as HD 35155.

#### 4. THE COMPACT COMPANION

To infer the temperature of the compact companion, one can in principle (a) compare the wavelength distribution of the observed continuous flux to that of either synthetic spectra from model atmospheres or that of observed white dwarfs whose temperatures are known, as was done for the WD in  $\alpha^1$  Ori (Ake & Johnson 1988), or (b) compare the profile of the absorption wing of the Lyman- $\alpha$  line with corresponding features predicted from a set of model atmospheres. To obtain the energy flux curve of the companion, we subtract the scaled flux

TABLE 5  
LW REGION EMISSION-LINE FLUXES  
( $10^{-13}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$ )

Image Number	Mg II $\lambda 2800$	C II $\lambda 2325$
LWR 14924/8.....	29.5	2.75
LWR 15008 <sup>a</sup> .....	29.2	...
LWR 16528/9.....	25.7	2.26
LWR 16715/6.....	29.3	3.25
LWR 17305/6.....	31.2	3.7::
LWR 17334/8 <sup>a</sup> .....	23.6	...
LWR 17337.....	> 27.8	4.34
LWR 5239/40.....	35.4	4.7:
LWR 12082.....	> 36.6	7.25::
LWR 12131.....	> 41.6	5.64

<sup>a</sup> High-dispersion spectra.

of a similar isolated S star (HR 8714) from the observed flux of HD 35155.

An immediate obstacle in applying the first method of HD 35155 is the jagged appearance of the spectrum due to the great strengths of the emission lines, which renders quite uncertain the placement of the continuum. Of more consequence is the fact that the observed ultraviolet flux from 1300 to 3300 Å roughly fits a  $f_\lambda \sim \lambda^{-1}$  law, which is far from that ( $f_\lambda \sim \lambda^{-4}$ ) expected from the Rayleigh-Jeans portion of a hot blackbody. It is closer too, but still not in agreement with, that expected from a steady state accretion disk,  $f_\lambda \sim \lambda^{-2.33}$ . Yet a definite decrease in the flux occurs shortward of 1300 Å, and this has the appearance of a short-wavelength exponential dropoff in the flux of a blackbody. A white dwarf with a temperature near 16,000 K or a main-sequence B star of 12,000–15,000 K gives the best fit to the turnover in the ultraviolet flux curve (Fig. 3). None of these, however, can reproduce the flux in the SW and LW regions simultaneously. There is always a flux surplus longward of 2000 Å. Because of the shape of the spectrum and

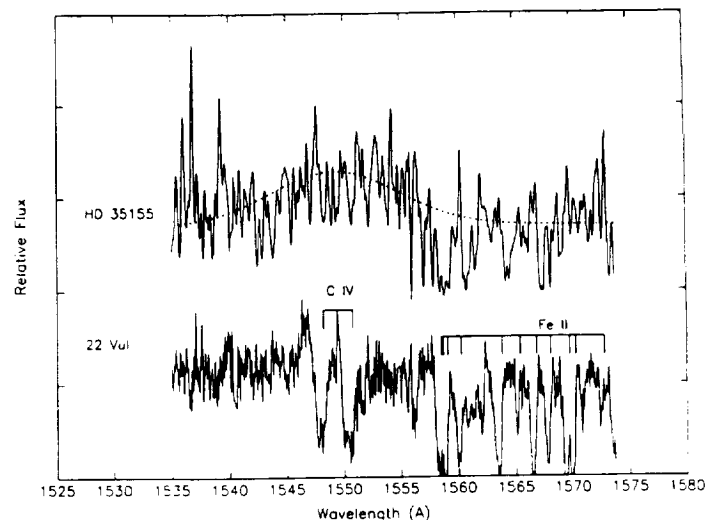


FIG. 6.—High-dispersion spectrum of the C IV region of HD 35155 (upper) and the  $\zeta$  Aur system 22 Vul in partial eclipse (lower), as taken by one of the authors (TBA). Strong Fe II absorption features from the G star's atmosphere in 22 Vul are indicated, as well as the reversed P Cyg profiles in C IV seen at this phase. In HD 35155, the C IV lines are rotationally broadened by at least 2500  $\text{km s}^{-1}$  (dotted line).

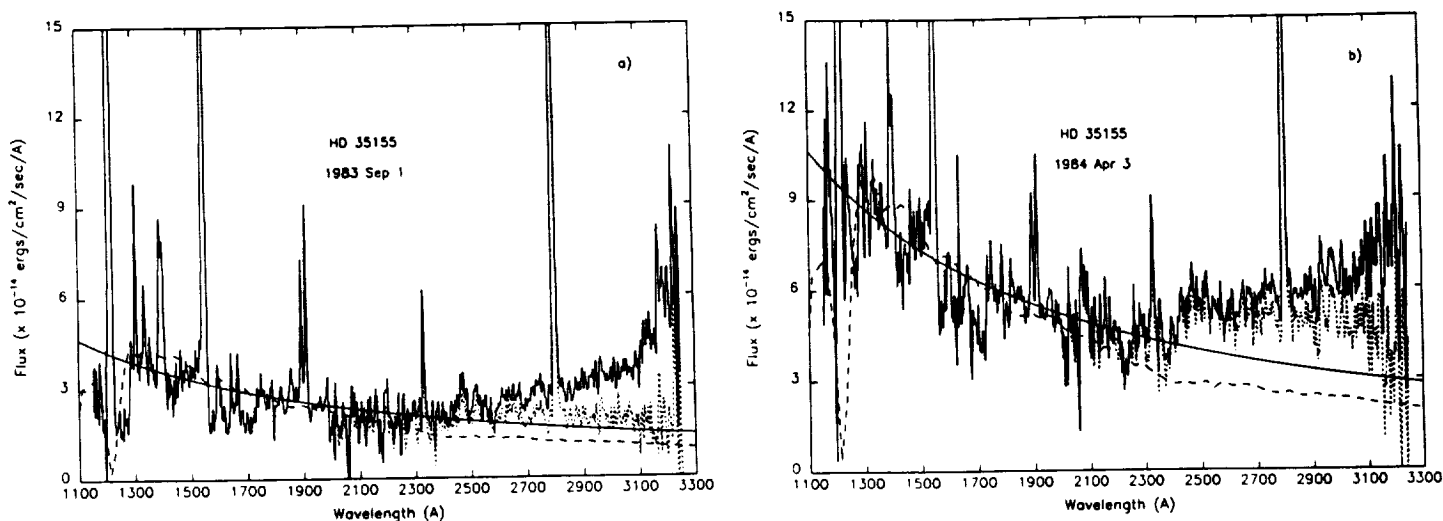


FIG. 3.—HD 35155 at a low (a) and high (b) excitation state. Dotted lines show the spectrum corrected for the S star primary by subtracting a scaled spectrum of the S4+/I<sup>+</sup> star HR 8714. Power-law curves from Table 3 are shown as solid lines. Dashed lines are model fluxes from Kurucz (1979) for a 13000 K,  $\log g = 4.5$  star normalized at 1950 Å.

(Reimers & Cassatella 1985). C IV must be produced in a hotter, rapidly rotating inner part of an accretion disk.

In the three LWR spectra, the Mg II *h* and *k* lines have a redward component (Fig. 8). While they may be badly mutilated by intervening circumstellar material, such as in the ordinary, single N-type carbon star TX Psc (Eriksson et al. 1986) as well as the interacting carbon star HD 59643 (Johnson et al. 1988), this profile is more characteristic of mass outflow from the system. In the three spectra, the profiles were essentially identical, although since two of the spectra were obtained within 2 days of each other, we have really only sampled the star at two epochs. This is unlike the situation of HD 59643, where changes in the Mg II profile suggest that the mass flow may be episodic.

Radial velocities of the Si III] and C III] lines are almost identical at  $+60 \text{ km s}^{-1}$ . Velocity measurements of the S star by Keenan & Teske (1956), Beavers & Eitter (1987), and Brown

et al. (1990) span the range from 68.5 to 98.6  $\text{km s}^{-1}$ . The suggestion by these workers that HD 35155 is a velocity variable has since been confirmed in detail: it is a binary star with an orbital period of  $637.5 \pm 7.4$  days (Jorissen & Mayor 1991). Though not conclusive, the Si III] and C III] velocities probably represent the velocity of the cloud or the companion, and not that of the giant star itself.

We note that a significant feature is missing from the spectrum, He II  $\lambda 1640$ . If, as is usually assumed (Zirin 1976; O'Brien & Lambert 1986),  $\lambda 1640$  is excited by X-rays, its absence indicates an absence of X-radiation and of regions hot enough to produce X-rays in sufficient quantities. If there is a very hot region in the inner part of the accretion disk, it must be too small or too heavily shielded to provide the necessary X-rays. Furthermore we infer that the Lyman  $\alpha$  line of He II at 304 Å is optically thin, for otherwise the population of the  $n = 2$  level of He II would build up sufficiently so that  $\lambda 1640$  would appear.

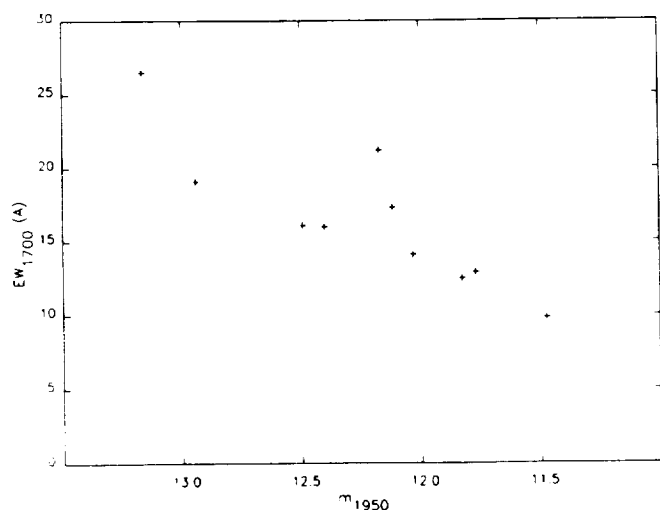


FIG. 4.—The equivalent width of the 1670–1730 Å absorption trough in HD 35155 vs. the magnitude at 1950 Å, where  $m_{1950} = -2.5 \log (F_{1950}) - 21.1$ .

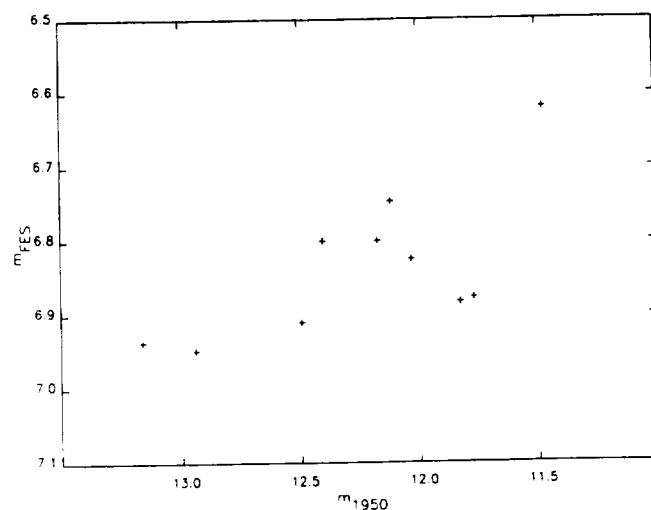


FIG. 5.—The V magnitude of HD 35155 as measured with the FES (Table 1) vs. the magnitude at 1950 Å (as in Fig. 4).

therefore follow closely that analysis, and the reader is referred to that paper for certain details omitted here.

Based on calculations of emission-line ratios (Nussbaumer & Schild 1979; Nussbaumer 1986) and of ionization equilibrium for symbiotic stars (Nussbaumer & Stencel 1987), we calculate values of the electron densities from the flux ratio of the intersystem Si III]  $\lambda$ 1892 and C III]  $\lambda$ 1909. Other lines may provide additional constraints on this value. If we assume nebular conditions, we can obtain the emission measure  $\langle n_e^2 \rangle \Delta V$  from the luminosity of  $\lambda$ 1909 and the known collisional rates (Dufton et al. 1978). Since the electron density is known, the volume of the C III]–emitting gas can be computed. By a different calculation one can also infer the emission measure of C IV (Reimers & Cassatella 1985), but there is no independent method of obtaining the electron density in this case. The electron temperature is very difficult to obtain. For similar systems, temperatures are often in the range 10,000–20,000 K (cf. Nussbaumer & Stencel 1987).

The intersystem lines of C III] and Si III] are well-known diagnostics for the electron density. Although the ratio of C III]  $\lambda$ 1907/ $\lambda$ 1909 is sensitive to density, the weaker  $\lambda$ 1907 was not detected here (Fig. 7). Calculations of the flux ratios of (Si III]  $\lambda$ 1892)/(C III]  $\lambda$ 1909) for a range of temperatures and densities, based on the assumption of collisional excitation and radiative de-excitation in a homogeneous region are available (Keenan, Dufton, & Kingston 1987; Nussbaumer & Stencel 1987). To the extent these conditions hold for HD 35155, we derive values for the electron density in the line-forming region.

Values of  $\Lambda = \text{flux}(\text{Si III]})/\text{flux}(\text{C III]})$  for our 10 spectra are rather evenly distributed over the range 0.55–0.92. Although there is no direct diagnostic for the electron temperature, values of 10,000–20,000 K result from almost all allowable values of the temperature of the exciting star and of a wide range of electron densities. Because the excitation in HD 35155 is obviously less than that in symbiotics, the white dwarf must be cooler, and we choose  $T^* = 40,000$  K, the lowest value given by Nussbaumer & Stencel (1987). This leads in turn to a temperature  $T_e = 15,000$  K and to values of the fractional ionization ratio  $n(\text{Si III})/n(\text{Si})/n(\text{C III})/n(\text{C})$  of  $\sim 0.7$ .

To correct for the abundance peculiarities of this star, we use the results of Smith & Lambert (1990), who find that while HD 35155 has a carbon deficiency as seen in other evolved red giants due to CNO processing ( $[^{12}\text{C}/\text{H}] = -0.27$ ), it shows a carbon enhancement with respect to its metal abundance ( $[^{12}\text{C}/\text{M}] = +0.23$ ). The abundance-corrected values of  $\Lambda = 0.93$ –1.56 then lead to electron densities of  $\log n_e = 9.9$ –10.3, or  $n_e \approx 10^{10} \text{ cm}^{-3}$ . If the ionization ratio is taken as 0.5,  $n_e = 1.5$ – $3.2 \times 10^{10} \text{ cm}^{-3}$ . Alternately, the recent calculations of Keenan et al. (1987) for an electron temperature of 30,000 K (their lowest value) and an ionization ratio of 0.7 again lead to values of  $\log n_e = 10.1$ –10.4. Altogether, then, a value of electron density  $n_e \approx 1$ – $2 \times 10^{10} \text{ cm}^{-3}$  must be quite close to the truth. Other density-sensitive lines are not usable due to the low signal and high noise.

For comparison, we note that electron densities of  $10^8$ – $10^9 \text{ cm}^{-3}$  seem typical for the chromospheric emission regions of K–M giants (Judge 1986a, b; Eaton & Johnson 1988) and supergiants (Eaton 1988), while the Si III]– and C III]–emitting cloud in the carbon star HD 59643 has a value near  $10^{10} \text{ cm}^{-3}$ .

Values of  $\Lambda$  for various symbiotic stars are in the range 0.2–1.0 (Nussbaumer & Stencel 1987). These authors point out the possible existence of a cutoff in these values near 0.75–1.00, which occurs near  $n_e = 10^{10} \text{ cm}^{-3}$ , and they suggest this may

TABLE 7  
VALUES OF ELECTRON DENSITY ( $N_e$ ) AND VOLUME ( $\Delta V$ )

SWP IMAGE NUMBER	$L(\text{C III])}_0$ ( $10^{30} \text{ ergs s}^{-1}$ )	Si III]/C III]	$T_e = 15,000 \text{ K}$	
			$N_e$ ( $10^{10} \text{ cm}^{-3}$ )	$\Delta V$ ( $10^{34} \text{ cm}^3$ )
18957.....	8.06	0.66	1.16	6.10
20615.....	4.66	0.84	1.68	1.68
20878.....	9.14	0.73	1.36	5.07
22522.....	7.40	0.75	1.41	3.78
22638.....	13.8	0.62	1.05	12.7
22656.....	9.18	0.92	1.94	2.50
24937.....	5.60	0.87	1.78	1.81
32352.....	30.3	0.57	0.93	36.0
32376.....	14.3	0.55	0.88	19.0
32351.....	19.9	0.64	1.11	16.6

signal the operation of a new physical mechanism that inhibits cooling and leads to a rapid rise in  $T_e$  and  $P$ . The resultant expansion would provide a straightforward explanation for the apparent cutoff. It may well be that HD 35155 and HD 59643 are at or near that critical value.

As for HD 59643, we can obtain the emission measure,  $\int n_e^2 dV = \langle n_e^2 \rangle \Delta V$ , from the luminosity of C III]  $\lambda$ 1909, if we assume nebular conditions (low optical depth) and homogeneity of the emitting region (cf. Johnson et al. 1988). Hydrogen will be fully ionized in any region with doubly ionized carbon, and therefore the hydrogen (proton) density equals the (known) electron density. Thus the densities of the dominant ions of all other species scale as the atomic abundances. Assuming collisional excitation and radiative deexcitation of the upper level, one finds that  $\langle n_e^2 \rangle \Delta V C A_C h\nu = L(\text{C III])}_0$ , where  $L(\text{C III])}_0$  is the reddening-corrected ( $\times 1.25$ ) absolute flux of  $\lambda$ 1909,  $A_C$  is the abundance of carbon relative to hydrogen,  $C$  is the collisional excitation rate, and carbon is assumed to be doubly ionized. We take  $A_C = 2.5 \times 10^{-4}$ , and use the distance and reddening determined by Eggen. By extrapolating the collisional excitation rates of Dufton et al. (1978) to 15,000 K, we find  $C = 3.8 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1}$ . We compute  $n_e$ ,  $\langle n_e^2 \rangle \Delta V$ , and finally  $\Delta V$  of the emitting region at each observed epoch (Table 7), and we find  $\Delta V = 1 \times 10^{35} \text{ cm}^3$  within a factor of about 4–5, or with that much variation, as shown in Table 7. If spherical and homogeneous, the region emitting C III] and Si III] has a radius of about  $R = 3 \times 10^6 \text{ km} = 4 R_\odot$ . The uncertainty in distance would change this by a factor of 30%, well within the other uncertainties.

Following Reimers & Cassatella (1985), who studied the wind accretion onto Mira B, we estimate the emission measure of the C IV resonance doublet from the observed line flux. This treatment incorporates the assumption that the emission is effectively optically thin, so that every collisional excitation to the upper level of an allowed transition results in a photon in that transition (cf. Pottasch 1964). Applying these results to HD 35155, we find  $\langle n_e^2 \rangle \Delta V = 1.1 \times 10^{54} \text{ cm}^{-3}$ . Unfortunately, because there is no independent way of estimating the electron density in the C IV region, we cannot deduce the emitting volume.

Finally we note that H $\alpha$  Balmer-line emission has been observed in HD 35155 (V. V. Smith 1988; private communication; B. W. Bopp 1990, private communication). These observations make HD 35155 appear even more similar to the symbiotic stars, which characteristically show Balmer-line emission (Kenyon 1986).

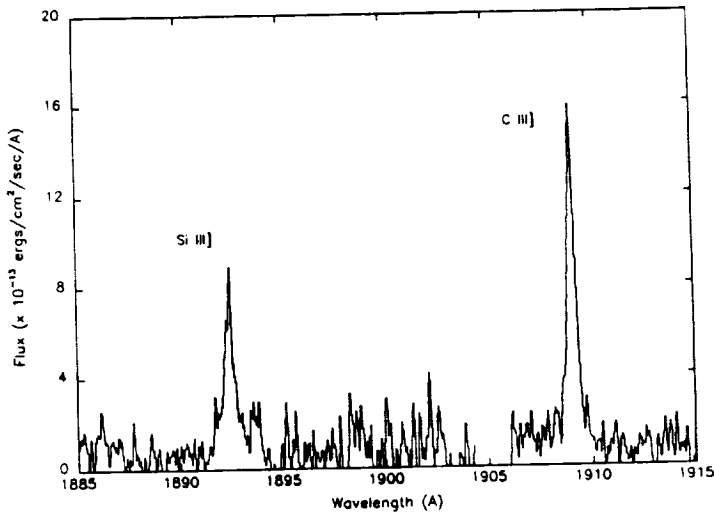


FIG. 7.—High-dispersion spectrum of the Si III and C III lines

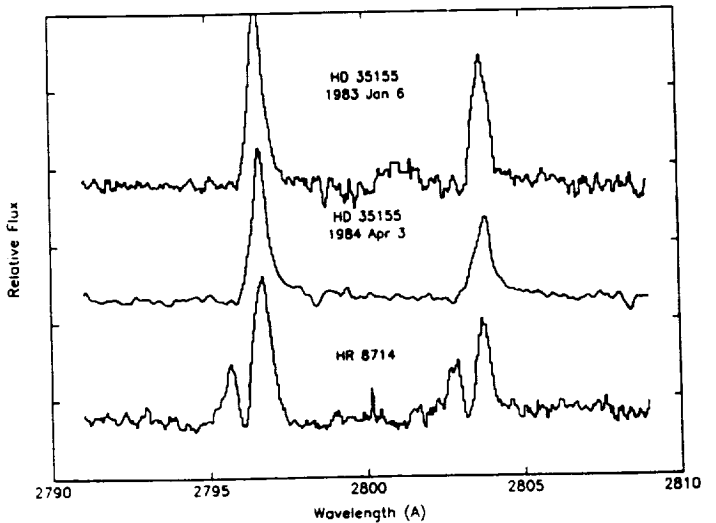


FIG. 8.—High-dispersion spectra of Mg II h and k at two phases of HD 35155 (upper) and the S star HR 8714 (lower).

the overlying absorption features, it is simply impossible to estimate a proper color temperature of the companion, and the above crude estimate is the best that can be given. A multiple-temperature model is needed to adequately represent the full continuum.

An attempt to infer the temperature of the compact companion from a fit of the wings of Lyman-alpha to either *IUE* observations of single white dwarfs or to theoretical predictions from a set of model atmospheres appears impossible due to the filling in of the wings by emission. The blue wing contains two strong, blended emission lines at 1160, 1175 Å—the latter due to C III—plus a weaker line at 1183 Å. Worse yet is a resau at 1190–95 Å. Only for a very few angstroms near 1181 is the line wing seen, and this interval is too short to yield a meaningful slope.

A deeper problem is whether the photosphere of the hot star is ever seen. Choosing the fluxes from the spectrum (SWP 20878) on which the ultraviolet emission is weakest (all the flux above that minimum level being assumed to come from the gas cloud), we measure the observed (integrated) excess continuous flux between 1300 and 3300 Å as  $5 \times 10^{-11}$  ergs cm $^{-2}$  s $^{-1}$ . At a distance of 372 pc, this leads directly to a luminosity of  $8 \times 10^{32}$  ergs s $^{-1}$  = 0.2  $L_{\odot}$ —far too high for a white dwarf. An uncertainty in the distance of a factor of 1.5 does not reverse this conclusion. Apparently, then, even in the quiescent state, much of the ultraviolet emission arises from sources other than the photospheres of the white dwarf or the red giant.

Finally we note that at the brightest phases the Fe II absorption features are the weakest. This could indicate that the

variations are due to changes in obscuring material in the vicinity of the secondary. During periods of high obscuration, the overall UV flux drops and the absorption spectrum deepens. The UV emission lines, however, do not follow this behavior. It may be more likely that the absorption occurs at the outer, cooler edge of the accretion disk, which is disrupted at periods of bright outburst.

### 5. THE GAS CLOUD

Symbiotic stars typically consist of three components: a cool giant, a hotter companion, and a gas cloud. The hotter companion may either be a hot subdwarf, an accreting white dwarf, or an accreting main sequence star. HD 35155 resembles symbiotics in its three components and the high excitation lines in the ultraviolet.

We can imagine three possible locations/mechanisms for the hot gas: (1) the chromosphere (or a sector of the chromosphere) of the present primary (S star) heated by X-rays from the secondary; (2) an accretion disk around the companion; (3) X-ray illumination of a cloud or stream of gas. We examine each of these alternatives. Our conjectures are relatively limited since no X-rays have been detected from HD 35155. It was missed on the *Uhuru* and *Einstein* surveys. The absence of He II  $\lambda 1640$ , which seems to indicate the absence of copious quantities of X-rays, seems to provide some evidence against both mechanisms (1) and (3).

In several respects the S star HD 35155 closely resembles the cool carbon star HD 59643, which has recently been investigated as an interacting binary system (Johnson et al. 1988). We

TABLE 6  
HIGH-DISPERSION VELOCITIES

IMAGE NUMBER	$V_{\text{rad}}$ (km s $^{-1}$ )			FWHM (km s $^{-1}$ )			
	Mg II	Si III]	C III]	Mg II	Si III]	C III]	C IV
SWP 22638 .....	...	+ 60.5	+ 59.0	...	103	73	~ 2500
LWR 15088 .....	115.8 $\pm$ 4.2	...	...	Blue cutoff	...	...	...
LWR 17334 .....	116.3 $\pm$ 1.4	...	...	Blue cutoff	...	...	...
LWR 17338 .....	119.2 $\pm$ 4.2	...	...	Blue cutoff	...	...	...

## 6. DISCUSSION AND CONCLUSIONS

S stars may well represent a wide variety of evolutionary histories. Current wisdom (Johnson & Ake 1986; Peery 1986; Smith & Lambert 1985, 1987; Little, Little-Marenin, & Bauer 1987; Brown et al. 1990) suggest that at least two types of histories can be distinguished observationally. "Real" or "true" S stars have their enhancements of *s*-process elements and carbon from the third dredge-up within the AGB star itself. "Accidental" S stars are cooler analogs of the Ba stars or simply evolved Ba stars; they are binaries consisting of a giant and a post-AGB star (hot subdwarf or white dwarf). In these systems the present primary star (the giant) received its abundance peculiarities by mass transfer at a much earlier epoch when its companion was itself an AGB star. The element Tc, whose longest lived *s*-process isotope—<sup>99</sup>Tc—has a half-life of only  $2 \times 10^5$  yr, provides a vital clue to distinguishing between these two scenarios. Once dredge-up of *s*-process elements (including Tc) begins in a star, the dredge-up episodes occur with periods of  $50\text{--}100 \times 10^3$  yr—far less than the half-life of Tc, so that Tc will always be found on the stellar surface of a true S star. If *s*-process elements were transferred from a companion, on the other hand, Tc will almost surely have disappeared, so that accidental S stars will have an enrichment of heavy elements but no Tc (Little-Marenin 1989).

This possible scenario has been greatly strengthened recently by (1) the observation of He I 10830 Å in all seven Tc-deficient S and MS stars and only one of 13 Tc-showing S and MS stars observed by Brown et al. (1990), and the additional factor that the first group shows large radial velocity variations and (2) by the direct observation of white dwarf companions to several Tc-deficient S and MS stars while finding far fewer among Tc-showing stars (Johnson, Ake, & Ameen 1991).

The unusual S star HD 35155 is in the accidental S star category; it shows no Tc (Peery 1971; Smith & Lambert 1988), and we have detected not only the companion but have also found that it is still interacting with the primary!

By means of both low-resolution and high-resolution *IUE* spectra, we investigate the chromosphere and circumstellar region of HD 35155. Assuming a distance, we calculate the luminosities in the observed ultraviolet emission lines (Table 4). HD 35155 shows, in addition to the usual low-excitation emission lines (O I, Mg II, Fe II), the semiforbidden C III] and Si III] lines near 1900 Å and the C IV resonance doublet. We have deduced the electron density ( $\sim 10^{10} \text{ cm}^{-3}$ ) in the region responsible for the C III] and Si III] lines. However, the much greater width of C IV  $\lambda 1550$  indicates it is formed in a hotter region with much higher velocities, probably in the inner edge of an accretion disk.

We present evidence in this paper for the following conclusions and comments.

1. The ultraviolet continuum appears to be formed in a variable accretion disk being fed by the outer atmosphere and wind from the S star. Although this is the most straightforward hypothesis and such disks are suspected in a wide variety of binaries, there is no other reason to believe such a strong wind would be flowing from this particular star.
2. The variability of the UV continuous emission demonstrates that it comes from the chromosphere of the giant or a gas cloud and not from the photosphere of either component.
3. At the same time the brightness of the ultraviolet continuous flux, even at the faintest recorded epoch, yields, with the known distance, the luminosity  $L = 0.2 L_{\odot}$ , far too great for a white dwarf. This reinforces the conclusion that most of the

ultraviolet continuum originates from the gas cloud and not with the photosphere of the companion.

4. Although some absorption lines are present, these may be seen against an optically thick cloud or the edge of the disk. There is no convincing evidence that the photosphere of the companion is seen.

5. The strength of chromospheric lines in HD 35155—much greater than in single cool giants (Ayres, Marstad, & Linsky 1981; Steiman-Cameron et al. 1985)—seems to rule out their production by the giant's chromosphere unless it is illuminated by energetic X-radiation from the companion, and the absence of He II 1640 Å appears to rule out that possibility. Wind collisions or shocks due to the interaction of the hot secondary with intrasystem material are possible excitation mechanisms and should be investigated with observations at appropriate orbital phases. The extreme broadening of the C IV doublet, however, requires its source elsewhere in any case. We favor the binary hypothesis, with Mg II and C II being partially produced in the chromosphere of the S star, C III] and Si III] being produced in a gas cloud, and C IV being produced in the inner part of an accretion disk.

The HD 35155 system is clearly of considerable interest from several points of view. It is an interactive binary system involving an S star, and the excited matter, which has presumably flowed from the S star, is of nonsolar composition. It appears to be a perfect example for an S star whose abundance peculiarities were produced by mass transfer during a previous epoch when the present hot companion was itself an AGB star—an "accidental" PRG star. Such a system would be cooler and more evolutionarily advanced than a barium star, for which the mass transfer hypothesis appears so attractive (McClure 1989; Jorissen & Mayor 1988; Smith & Lambert 1988). This conclusion regarding HD 35155 is based on the following pieces of evidence. (1) HD 35255 shows no detectable lines of Tc I and therefore apparently has no Tc (Little et al. 1987; Smith & Lambert 1988). According to our present understanding of the third dredge-up, then, HD 35155 is not a thermally pulsing AGB star. This conclusion is reinforced by the additional fact that the primary star appears to be nonvariable. (2) Without question HD 35155 is enriched in *s*-process elements (Smith & Lambert 1990). Since the present giant is not dredging up (and presumably has never dredged up) *s*-process matter, the *s*-process matter must have come from a companion. (3) A hot companion has been discovered (this paper) and its properties indicate strongly (perhaps not conclusively) that it is a white dwarf or hot subdwarf; that is, a post-AGB star. (4) That the system is presently interacting (this paper) is doubly interesting, in that it demonstrates convincingly that the stars are close enough to have interacted in the past, and it provides a unique situation in which the wind, stream, cloud, or disk is composed of material from an S star with composition different from the Sun.

Further observations of this unusual object should prove very rewarding, especially the following. Other nonvariable Tc-deficient S and MS stars should be observed with *IUE* for the presence of hot, compact companions (Peery 1986; Johnson & Ake 1986; Johnson et al. 1991). Additional observations should be made of HD 35155 with *IUE* to determine to what extent the spectrum is variable and to be alert for periods of outflow of matter signaled by the Mg II lines. It would be of interest to observe the star both in the X-ray and radio region of the spectrum. Observations of Balmer lines would also be very valuable. Further orbital phase coverage could help establish the location of the line and continuum forming regions.

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16. Abstract  IUE Observations were begun for a two-year program to monitor the UV variability of three interacting peculiar red giant (PRG) binaries, HD 59643 (C6,2), HD 35155 (S3/2), and HR 1105 (S3.5/2.5). All of these systems were suspected to involve accretion of material from the PRG to a white-dwarf secondary, based mainly on previous IUE investigations. From our earlier surveys of PRGs, they were primary candidates to test the hypothesis that Tc-poor PRGs are formed as a result of mass transfer from a secondary component rather than from internal thermal pulsing while on the asymptotic red giant branch.					
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